

## Multiphase Boost Converter with Reduced Input Current Ripple Using Direct Coupled Inductors

G. Kishor\*, D. Subbarayudu\*\*, S. Sivanagaraju\*\*\*

\*Associate Professor, Department of EEE, GPREC, Kurnool

\*\* Retd. Professor & HOD, Department of EEE, GPREC, Kurnool

\*\*\* Professor & HOD, Department of EEE, JNTUK, Kakinada

### ABSTRACT

The multi phase Boost topology is very popular in many applications. However, the current ripple in the input inductor affects its ability to meet EMI requirements. This paper presents the concept of overall current ripple reduction of multiphase DC-DC converter by employing directly coupled inductors. An emphasis was also given to calculate the generalized expression of equivalent inductance. With the help of specified parameters, the design parameters are also determined. The proposed multi phase Boost topology retains the advantages of the conventional Boost topology, but with ripple free input current. Detailed analysis was validated with simulation and the results have been presented.

**Keywords** – Multiphase Boost Converter, Direct coupled, Ripple reduction.

### I. INTRODUCTION

Switching power converters have become more and more important in industry today. Coupled inductor and integrated magnetic techniques have been widely reported since they were implemented in the Cuk converter in 1977. The advantages of integrated magnetic techniques are that the amount of core material is reduced and the component count is reduced. The significant advantage is that the ripple in one winding can be dumped to another winding, thus achieving a ripple free input or output current by using coupled inductor technique. In addition to the ripple free input current, Sepic and Cuk converters also have the advantage of overload protection since there is one capacitor, in the main loop to transfer the energy. However, this capacitor has to carry large input and output currents with a dc voltage value in each cycle. The switch voltage stress of the Sepic and Cuk converters is the sum of the input voltage and the output voltage. This is a very critical condition in some applications, especially for “boost” only applications.

To meet the relevant EMI requirements in power electronics a ripple free input current is very much essential. A Boost-buck cascaded converter is used for ripple reduction [1], however one addition buck converter is used which increases the cost. Several input filter designs are analyzed and implemented [2], which increases the size of the inductor used. However, the Cuk and Sepic converters can easily achieve zero-ripple input current by using coupled inductor techniques. Therefore, the input current harmonics are much less

than the PWM Boost converter and EMI is much better [3].

Coupled-inductor and other integrated-magnetics techniques have existed for many years, but most power electronics engineers are uncomfortable with them. This may be because of limited experience with coupled magnetics. Or it could be explained by the level of complexity in many treatments of coupled magnetic devices. Unlike most networks, coupled-inductor techniques involve simultaneous parallel energy-transfer pathways: electrical and magnetic. Despite the difficulty, the circuits are useful and deserve to be better appreciated.

Multiphase structure with interleaved control is essential for the boost converter in order to reduce the ripple current and to reduce the size of passive component. On the other hand, although parallel individual DC-DC converters in interleaved structure have been demonstrated to reduce the overall current ripple, it is still challenging to meet today's requirements. In addition, the multiphase interleaving structure has more inductors than the single phase converters, which increases the complexity of this converter. Solution has to be found to reduce the core number and the complexity of converters. This paper is aimed to improve the performance of multiphase DC-DC converters by employing directly coupled inductors.

### II. TWO PHASE BOOST CONVERTER

To increase the output voltage level a multiphase boost converter is used. Fig.1 shows the

schematic diagram of a two phase boost converter with directly coupled inductors. The coupled inductors are used to reduce the current ripple. In the circuit shown switch  $SW_1$ , inductor  $L_1$  and the diode  $D_1$  acts as one phase of boost converter. Similarly switch  $SW_2$ , inductor  $L_2$  and the diode  $D_2$  acts as the other phase of boost converter.

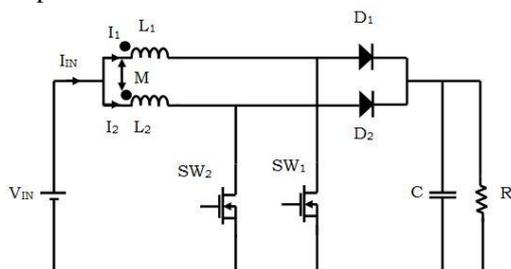


Fig. 1. Two phase Boost converter

Fig. 2 shows the equivalent circuit of directly coupled inductors

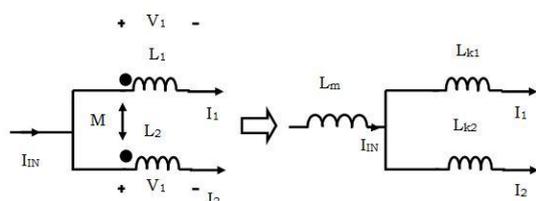


Fig. 2. Equivalent circuit of directly coupled inductors

Where  $L_{k1}$  and  $L_{k2}$  are the leakage inductances and  $L_m$  is the mutual inductance. The coupled inductors are related with the equation (1)

$$L_m = \alpha \sqrt{L_1 L_2} \quad (1)$$

Where  $L_1$  and  $L_2$  are the inductances of the two inductors. Let  $L_1 = L_2 = L$  and  $L_{k1} = L_{k2} = L_k$ . Also let  $V_1$  and  $V_2$  are the voltages across the two inductors which is given as in equation (2).

$$\begin{aligned} V_1 &= L_1 \frac{dI_1}{dt} + L_m \frac{dI_2}{dt} \\ V_2 &= L_m \frac{dI_1}{dt} + L_2 \frac{dI_2}{dt} \end{aligned} \quad (2)$$

By rearranging the equation (2)

$$\begin{aligned} V_1 - \frac{L_m}{L} V_2 &= \left( L - \frac{L_m^2}{L} \right) \frac{dI_1}{dt} \\ V_2 - \frac{L_m}{L} V_1 &= \left( L - \frac{L_m^2}{L} \right) \frac{dI_2}{dt} \end{aligned} \quad (3)$$

Consider the gating signals for one switching cycle with  $V_{G1}$  and  $V_{G2}$  as gating signals of the two switches  $SW_1$  and  $SW_2$  as shown in Fig.3.

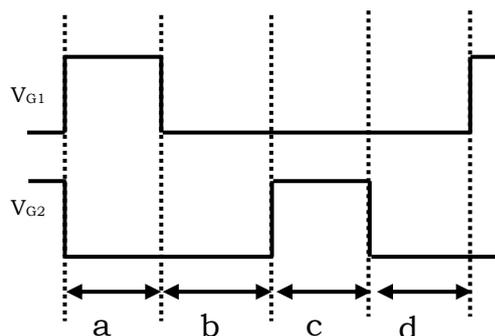


Fig.3. One switching cycle

Switch  $SW_1$  is on in the period 'a'. During this period switch  $SW_2$  is in off position and so  $V_1$  and  $V_2$  are given as

$$V_1 = V_{IN} \quad \& \quad V_2 = V_{IN} - V_0 \quad (4)$$

In this stage the multiphase boost converter act as single phase boost converter and so the output voltage is given as

$$V_O = \frac{V_{IN}}{(1-D)} \quad (5)$$

Substituting equation (5) in (4)  $V_2$  is given as

$$V_2 = -\frac{D}{(1-D)} V_1 \quad (6)$$

Substituting equation (6) in (3) and solving for  $V_1$  which gives

$$V_1 = \left[ \frac{L - \frac{L_m^2}{L}}{1 + \frac{L_m}{L} \cdot \frac{D}{(1-D)}} \right] \frac{dI_1}{dt} \quad (7)$$

Therefore the equivalent inductance during the period 'a' is

$$L_{eq,a} = \frac{L - \frac{L_m^2}{L}}{1 + \frac{L_m}{L} \cdot \frac{D}{(1-D)}} = \frac{1 - \alpha^2}{1 + \alpha \frac{D}{(1-D)}} L \quad (8)$$

Where  $\alpha$  is coefficient of coupling and  $\alpha = L_m/L$ .

Similarly during the time interval 'b'  $V_1$  and  $V_2$  are given as

$$V_1 = V_{IN} - V_0 \quad \& \quad V_2 = V_{IN} - V_0 \quad (9)$$

From equation (9) it is clear that

$$V_1 = V_2 \quad (10)$$

Substituting equation (10) in (3), the equivalent inductance is

$$L_{eq,b} = (1 + \alpha) L \quad (11)$$

Similarly, during time interval 'c',  $V_1$  and  $V_2$  are

$$V_1 = V_{IN} - V_0 \quad \& \quad V_2 = V_{IN} \quad (12)$$

Therefore  $V_1$  and  $V_2$  are related with the equation given in (13)

$$V_2 = \frac{1-D}{D} V_1 \quad (13)$$

By substituting equation (13) in equation (3), the equivalent inductance  $L_{eq,c}$  is

$$L_{eq,c} = \frac{1 - \alpha^2}{1 + \alpha \cdot \frac{1-D}{D}} L \quad (14)$$

The interval 'd' is same as interval 'b' and so the equivalent inductance is

$$L_{eq,d} = (1 + \alpha) L \quad (15)$$

### III. RIPPLE CURRENT REDUCTION

For a duty cycle below 0.5 the phase current and overall current waveforms are as shown in Fig.4. The phase current ripples of phase 1 and phase 2 are given as

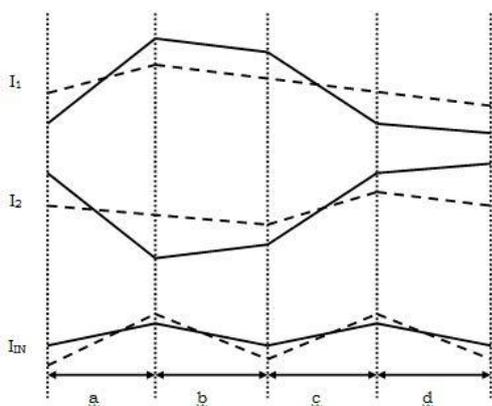


Fig.4. Current waveforms in one switching cycle

$$\Delta I_{1,a} = \frac{V_{IN}DT}{L_{eq,a}} = \frac{V_{IN}DT}{L} \cdot \frac{(1+\alpha) \cdot D}{1-\alpha^2} \quad (16)$$

$$\Delta I_{2,a} = \frac{(V_{IN} - V_0)DT}{L_{eq,a}} = \frac{V_{IN}DT}{L} \cdot \frac{\alpha + \frac{D}{1-D}}{1-\alpha^2} \quad (17)$$

The overall current ripple is the sum of two phase current ripples and for a directly coupled inductors it is given as

$$\Delta I_{IN,dir} = \Delta I_{1,a} + \Delta I_{2,a} = \frac{V_{IN}DT}{L} \cdot \frac{(1-2D)}{(1-D)} \cdot \frac{1}{(1+\alpha)} \quad (18)$$

Similarly the ripple current for a uncoupled inductors is given as

$$\Delta I_{IN,unc} = \frac{V_{IN}DT}{L} + \frac{(V_{IN} - V_0)DT}{L} = \frac{V_{IN}DT}{L} \cdot \frac{(1-2D)}{(1-D)} \quad (19)$$

With this the ratio of the direct coupled to the uncoupled is

$$\frac{\Delta I_{IN,dir}}{\Delta I_{IN,unc}} = \frac{1}{1 + \alpha} \quad (20)$$

With the variation in duty cycle and with coefficient of coupling  $\alpha = 0.61$ , Fig.5 shows the input current variation of uncoupled and the directly coupled inductors.

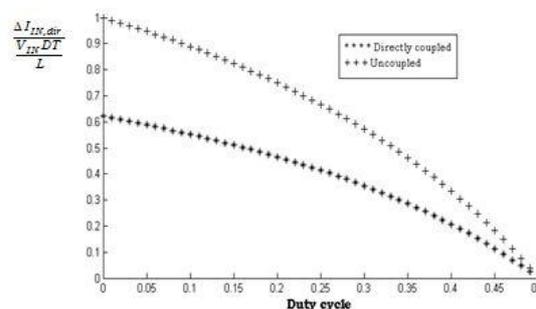


Fig.5. Input current reduction in uncoupled and directly coupled inductors

From the Fig.5 it is clear that by increasing the coupling coefficient, which effectively reduce the input current ripple. Therefore coupling coefficient is to be chosen carefully.

### IV. DESIGN PROCEDURE

The design procedure for the multiphase boost converter is presented in this section. The specifications of the boost converter are

Output Power	$P = 250W$
Output Voltage	$V_o = 200V$
Input Voltage	$V_{IN} = 50V$
Switching frequency	$f_s = 25kHz$
Input current ripple	$\Delta I = 10\%$ of phase current

The design procedure can be performed as following

Duty cycle  $D = 1 - \frac{V_{IN}}{V_o} = 0.75$

Input current  $= P/V_{IN} = 5A$

$$L_{eq,a} \geq \frac{V_{IN}DT}{\Delta I_{phase}} = 0.23mH$$

With the consideration of losses and high transient current, the inductors used are chosen with slight changes. In the proposed converter the maximum current that flow through the inductor in each phase is equal to half of the total current.

### V. SIMULATION RESULTS

In order to verify the theoretical analysis of the previous section, simulations have been carried out.

An input voltage of 50V given to the converter circuit and the switching pulses of duty ratio,  $D=0.74$  and frequency,  $f = 25$  kHz given to the MOSFET's is shown in Fig. 6, Fig.7 and Fig.8, respectively.

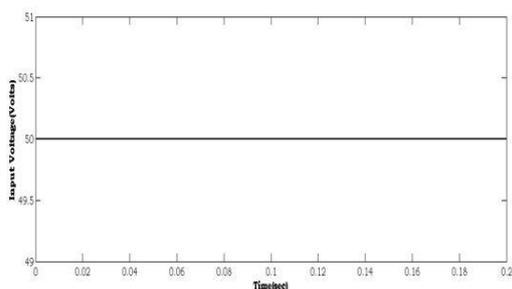


Fig.6 Input voltage to the converter

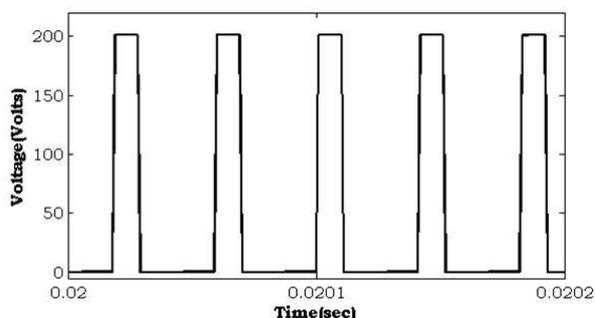


Fig.10 Voltage across the switch S2

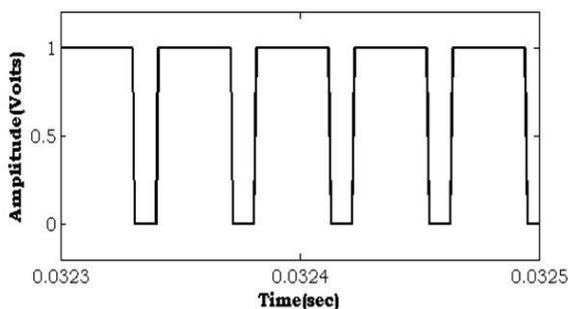


Fig.7 Driving pulses for switch S1

Fig. 9 and Fig. 10 shows the output voltages across the switches. It can be seen that the output of MOSFET is compliment of the input.

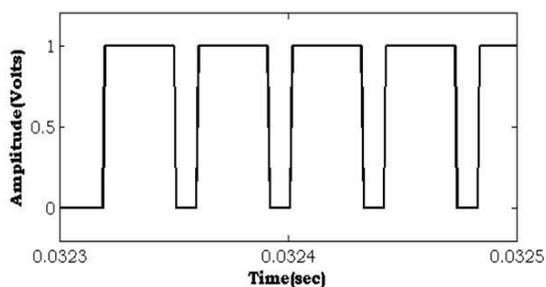


Fig. 8 Driving pulses for switch S2.

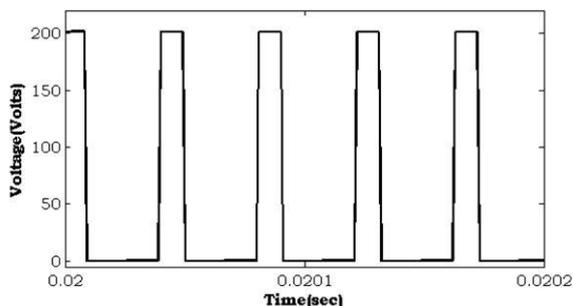


Fig.9 Voltage across the switch S1

Fig.11 and 12 shows the current waveforms of uncoupled and direct coupled. With uncoupled inductors, the input current has risen up to 24A and settles at 6.181A in 0.075sec whereas with direct coupling, the input current has risen up to 18.7A and settles at 6.07A in 0.06 seconds. Therefore the direct coupling method attains stability at a much faster rate compared to the converter with uncoupled inductors. A close observation of the two current waveforms (fig. 11 and fig.12) yields that the transient current has reduced along with the current ripple in directly coupled based two inductor boost converter system. The decrease in transient current ensures less harm to the inductor as well as the switches and moreover the rating of the inductor can be reduced, thus decreasing the size of the inductor. On the other hand the current ripple has reduced from 7.16% (as in uncoupled) to

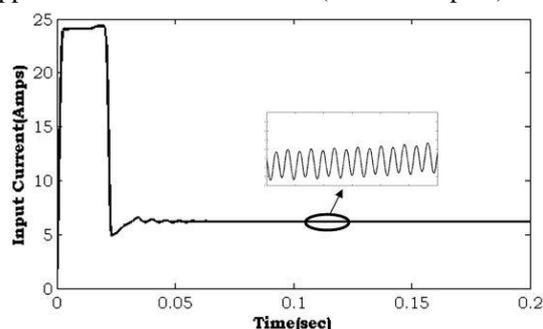


Fig.11 Input current for uncoupled system

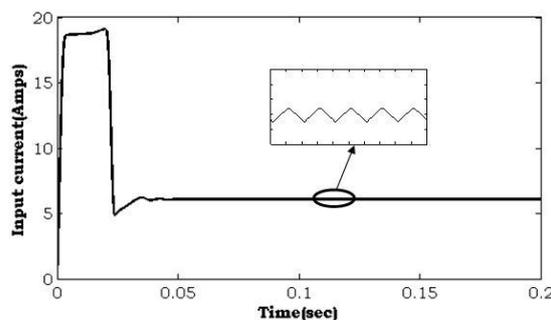


Fig.12 Input current for directly coupled system

6.58% (as in direct coupling), therefore the losses due to the ripple gets reduced, thus leading to an efficient converter.

In Fig. 13 and Fig. 14, the input power and output power of the system is shown. Clearly the input power is equal to the output power.

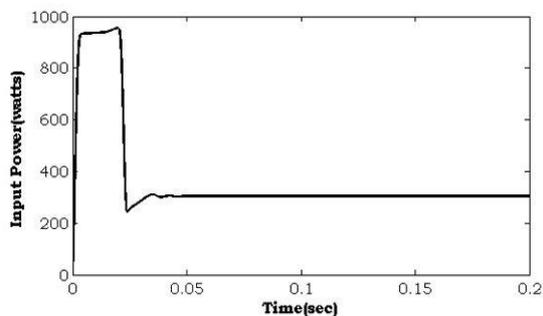


Fig.2.13 Input power of the system

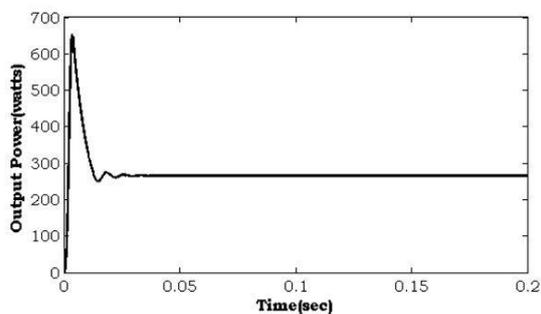


Fig. 14 Output power of the system

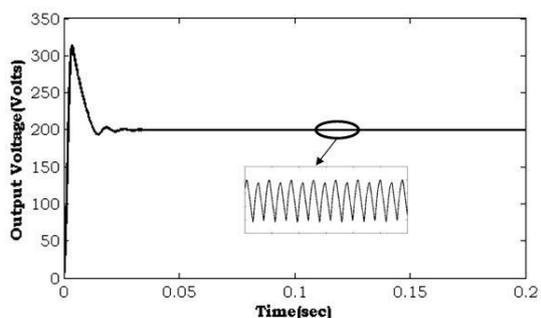


Fig.15 Output voltage of the system

Fig. 15 shows the output voltage which has settled at 199.5V. The output voltage ripple is found to be 0.76% which is clearly in the standard desired limits of 1%. Fig. 16 shows the output current of the system.

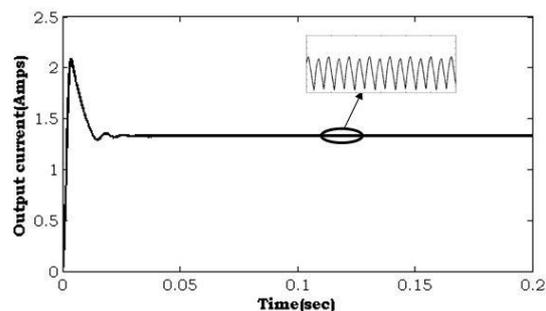


Fig.16 Output current of the system

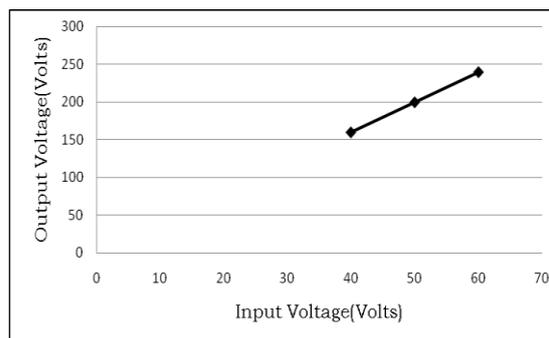


Fig.17 Variation of output voltage with input voltage

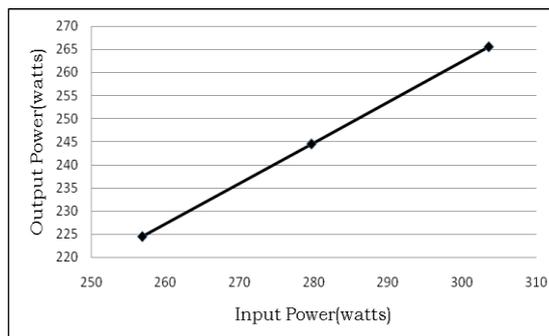


Fig.18 Variation of output power with input power

Fig. 17 shows the variation of the input voltage with the output voltage. Clearly, as desired, the output voltage is found to be four times the input voltage. Fig.18 shows the variation of the input power with the output power of the system. It can be observed that the efficiency lays around 86% for the direct coupled converter.

## VI. CONCLUSION

A multi phase boost converter is simulated with direct coupled inductors. The main feature of this circuit is that the voltage stress of each switch is one half of the voltage stresses of the switches in the single inductor implementation. In addition, the input current is distributed evenly through the two boost inductors so that the current ripple in the output capacitor is smaller than that in the single-inductor implementation. And also, it has been found that the

transient current has been reduced when compared with the uncoupled boost converter, thus minimizing the stress on inductor and the switches during transient period.

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